# Alpha-Particle Emission in the Decays of $B^{12}$ and $N^{12}$†

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Alpha particles following the beta decay of $B^{12}$ and the positron decay of $N^{12}$ to the region of $C^{12}$ above the 7.66-MeV state have been observed using a solid-state counter. The two alpha-particle spectra differ considerably in form and intensity but are completely consistent with one another within the assumption of charge symmetry. Since transitions to a possible admixed $T=1$ component in $C^{12}$ would be coherent with those to the chief $T=0$ component and since the matrix elements to these two components add in one decay and subtract in the other, the test of charge symmetry is quite sharp and it is shown that the intensity of the $T=1$ impurity may well be less than 1%. The branching ratios for the production of these high-energy alpha particles are $(7\pm2)\times10^{-4}$ and $(4.4\pm1.5)\times10^{-3}$ in the decay of $B^{12}$ and $N^{12}$, respectively. A reasonable account of the alpha-particle spectrum following $N^{12}$ decay (and so, by implication, following $B^{12}$ decay) is given by a single very broad $J=0^+$ level at a nominal resonance energy of 5.0 MeV above $Be^8+\alpha$ and a reduced width of 2.6 single-particle units ($3\hbar^2/2MR^2$). A better account is given by a broad level at lower excitation plus a level at about 11.8 MeV to which the $N^{12}$ beta decay has $\log ft\approx4.6$. The possible origin of the alpha-particle spectra in terms of the "ghost" of the 7.66-MeV state is considered and it is concluded that while such an effect may be quite considerable it is unlikely to account for the whole spectra as observed in this work.

## INTRODUCTION

THE beta decay of $B^{12}$ has been studied in considerable detail[1–3] and the main results as at present reported in the literature[4] are summarized in Fig. 1 together with the less-complete information[3,5,6] available on $N^{12}$. The most recent determinations of the half-lives are[7] $20.3\pm0.1$ msec for $B^{12}$ and $10.95\pm0.05$ msec for $N^{12}$.

We are here concerned with the transition from $B^{12}$ to a broad region in $C^{12}$ at an excitation of around 9–12 MeV that is followed by alpha-particle emission to the unstable ground state of $Be^8$. This results in an alpha-particle spectrum reaching up to between 2 and 3 MeV that has been measured in good energy resolution though from a rather thick source and with rather low statistics.[2] All that is known about the decay of $N^{12}$ that should populate this same region of $C^{12}$ is that it is followed by heavy-particle emission involving energies of the order of 4 MeV.[6] Considerably more energy is available in the $N^{12}$ decay than in the $B^{12}$ decay and so this region of high excitation in $C^{12}$ should be more strongly populated relative to the low-lying states by $N^{12}$ due to the approximate $W^5$ factor that occurs in the beta-decay probability, $W$ being the transition energy. Also because of the greater energy release, one stands a greater chance with $N^{12}$ than with $B^{12}$ of picking up transitions to $C^{12}$ states of higher excitation.

A specific interest in the decay to the 9–12 MeV region of $C^{12}$ is the possibility that the transition may not be to a genuine state of $C^{12}$ centered in this region but rather to the strongly distorted high-energy tail of the $J=0^+$ 7.66-MeV level to which $B^{12}$ decays[1] with a probability of $1.3\times10^{-2}$. Briefly the argument is[8] that the beta-decay probability will be proportional, among other things, to

$$\delta=\Gamma_\alpha/[(E-E_r)^2+\tfrac{1}{4}\Gamma_\alpha{}^2]$$

(in the approximation in which the level shift is taken as a linear function of energy across the resonance). Usually $\Gamma_\alpha$ will not change dramatically across a level and the population of the state by beta decay will reveal the familiar Breit-Wigner profile. If, however, the state is very near threshold, say just unbound, then $\Gamma_\alpha$ will be very tiny in the immediate region of $E_r$, but may increase by many orders of magnitude at a somewhat higher excitation—in the region where the outgoing alpha particle in the present illustration approaches the top of the Coulomb barrier. In these circumstances $\delta$ can increase with increasing $E$ at energies considerably above $E_r$ instead of falling monotonically and its integral over an extended range of $E$ well above $E_r$ may not be insignificant compared with the integral across $E_r$. If this happens, we may see a strong concentrated transition to $E_r$ followed by a gap and then a broad weak transition over a wide range of energy at higher

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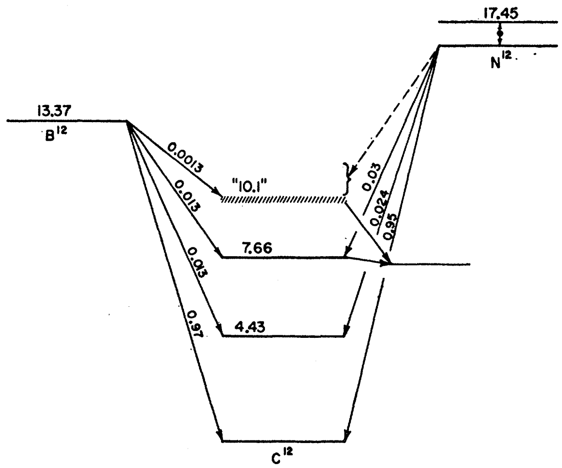


FIG. 1. Level scheme of $A=12$ showing branching ratios for $B^{12}$ and $N^{12}$ decay as reported in the literature. The excitations are in MeV.

excitation. This lower energy transition (to a region of higher excitation) is, thus, not to a new state in its own right but rather to the "ghost" of the state at $E_r$. The 7.66-MeV level of $C^{12}$ is unstable by only 0.28 MeV to break up into $Be^8+\alpha$ and so the observed weakly-populated broad region around 10 MeV reached in the beta decay of $B^{12}$ may possibly be its "ghost."[8] The intensity and excitation involved agree moderately well with the "ghost" expectation although the observed intensity appears to be somewhat too large. The $N^{12}$ beta decay should be much more favorable for this study since the $W^5$ factor there gives a stronger population of the "ghost" relative to the "real state" than for $B^{12}$ and also extends the population to significantly higher energies of excitation in $C^{12}$ so that the differences in spectral shape between the "ghost" of the 7.66-MeV state and an additional real state at about 10 MeV should be more readily detected.

A further point of specific interest in this work is the possibility that the $B^{12}$ and $N^{12}$ transitions to the broad 9–12 MeV region of $C^{12}$ may not be charge-symmetric. Whether we are dealing with a very broad real state or a "ghost," we must assume a very loose $\alpha+\alpha+\alpha$-like structure for $C^{12}$ in this region because, as we shall see, the reduced alpha-particle width is at least a single-particle unit, while the ground state of $Be^8$ itself has a reduced width of at least a single-particle unit for breakup into two alpha particles. The resulting picture of this region of $C^{12}$ is, therefore, one of three alpha particles barely hanging together. In this circumstance the Coulomb force between the alpha particles will be quite important for determining the over-all energy balance of the system, entering into the prescription of the state in an unusually significant way. It is usually said that isotopic spin is a good quantum number insofar as the Coulomb forces can be neglected in relation to the nuclear forces and one might, therefore, superficially expect that in the present circumstance the isotopic spin would be ill-defined, that the now-important Coulomb forces would introduce powerful $T=1$ components into the nominally $T=0$ system. This argument is not a good one, however, when the Coulomb force acts between self-conjugate subunits of an over-all self-conjugate system that are themselves individually strongly dominated by the nuclear force and are, therefore, individually rather pure from the point of view of isotopic spin. The isotopic spin purity of the over-all system is related by the Coulomb force only when that force acts in a way that distinguishes neutrons from protons; when the neutrons and protons are themselves locked together in subunits by the strong nuclear force, then the Coulomb force between the subunits effectively affects each subunit as a whole and the distinction of neutron from proton within each subunit is not important. It is, therefore, likely that the isotopic spin purity of this region of $C^{12}$ will be good if the extreme alpha-particle model is nearly valid but perhaps poor if the loose structure, in fact, contains significant amounts of "dissociated alpha particles." The question of the isotopic spin purity is, therefore, an interesting one. Even without this encouragement it is interesting to examine the charge symmetry of the $B^{12}$ and $N^{12}$ beta decays because of the mysterious large breakdown of charge symmetry that seems to obtain as between the ground-state transitions[7] [$ft$ for $B^{12}$ decay $=(1.17\pm0.012)\times10^4$; $ft$ for $N^{12}$ decay $=(1.33\pm0.027)\times10^4$] which is much greater than our present ideas about isotopic spin impurities seem able to explain. However, no such large breakdown is found for the transitions to the first excited state,[5] which may suggest that the trouble is in the ground state of $C^{12}$ rather than in $B^{12}$ and $N^{12}$. So information on transitions to other excited states of $C^{12}$ would be valuable. That on the decays to the 7.66-MeV state is not very accurate[1,3] but does not suggest any major breakdown.

## EXPERIMENT

The two active bodies were made in the reactions $B^{11}(d,p)B^{12}$ and $B^{10}(He^3,n)N^{12}$. The short half-lives involved precluded the transportation of the $B^{12}$ and $N^{12}$

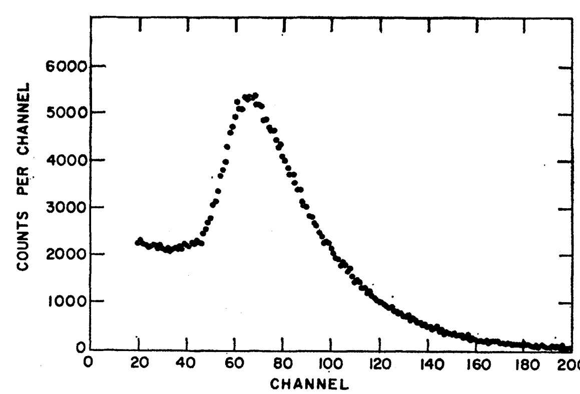


FIG. 2. Beta spectrum from $B^{12}$ decay as recorded in the plastic scintillator. The cutoff as normally imposed was at channel 31. The main peak is due to relativistic electrons that pass through the counter.

sources to a counter. Accordingly, a beam-chopper system was set up. The bombarding particles were produced by the Brookhaven Van de Graaff and were interrupted by a cylindrical shutter that rotated at 1800 rpm and gave a beam-on to beam-off ratio of 1:8 (two irradiations/revolution). Thirteen feet downstream from this chopper the target was located. The target was examined by a silicon solid-state counter of area 0.40 $cm^2$ at a distance of 1.52 cm from the target spot (itself a diam of 0.5 cm) and at right angles to the beam direction. The targets were slanted so that their normal made an angle of 60° to the beam. In order to avoid flooding the solid-state counter with elastically-scattered deuterons or $He^3$'s, a second shutter rotated between the target and the solid-state counter so that the counter saw the target only when the beam was interrupted by the first shutter. The two shutters were driven in synchronism by a Selsyn system.

For the work with $B^{12}$, the target thickness was 50 $\mu g/cm^2$; for that with $N^{12}$ the target thickness was 44 $\mu g/cm^2$. The backings were thick. The respective currents were 0.05 $\mu A$ and 0.07 $\mu A$.

The bias on the solid-state counter was adjusted so that its sensitive thickness was somewhat greater than the maximum range of alpha particles that could possibly be involved in the $C^{12}$ decay.

The target was also examined by a cylindrical plastic scintillator of diameter 4.5 cm and thickness 1.0 cm, at about 4 cm from the target. The plastic was shielded by sufficient aluminum to cut out beta radiations from bodies such as $N^{13}$ and $O^{15}$ made incidentally from the target substances themselves or from likely impurities.

A 5 in.×5 in. NaI(Tl) crystal with front face about 8 cm from the target completed the set of detectors that simultaneously examined the targets. This crystal was shielded from the target by $\frac{1}{8}$ in. brass and 2.0 cm aluminum which sufficed to reduce the direct effect on it of the $B^{12}$ and $N^{12}$ beta radiations to negligible proportions.

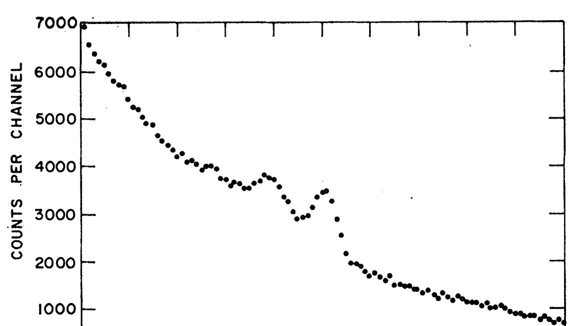


FIG. 3. Decay of $B^{12}$ as seen in the 5 in.×5 in. NaI(Tl) counter. The peaks at channels 101 and 89 are the full-energy and "one-escape" peaks of the 4.4-MeV gamma ray from the first excited state of $C^{12}$. The background on which these peaks are mounted is due partly to inner and outer bremsstrahlung and partly to the effects of neutrons produced by the intercepted deuteron beam and the general machine background.

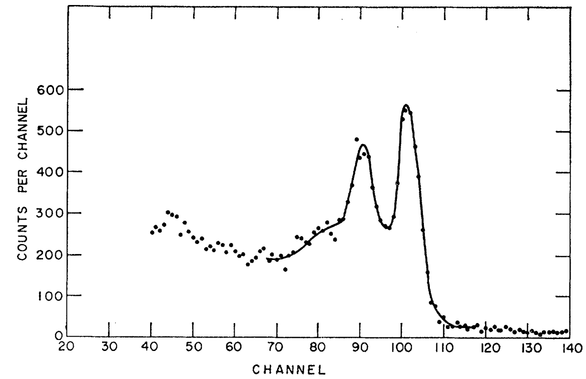


FIG. 4. Spectrum seen in the 5 in.×5 in. NaI(Tl) counter in coincidence with beta-particle pulses in the plastic scintillator. $B^{12}$ decay.

Throughout the normal running of the experiment with both sources the three detectors were simultaneously gated and the following regime was followed: irradiate 2 msec; wait 2 msec; count 12 msec; wait 2 msec; irradiate . . . .

The chief object of the experiment was to determine the energy spectrum and relative abundance of the alpha particles from the broad 9–12 MeV region of $C^{12}$ following the respective beta decays. The solid-state counter, which was checked and calibrated at frequent intervals using alpha particles from $Pu^{239}$, was of accurately known efficiency from direct measurements of its dimensions and distance from the target spot. The total source strengths with which we were dealing were determined through the efficiency of the plastic scintillator beta counter. This could not be calculated accurately because of the rather complicated geometry, the likely importance of scattering effects, and the fact that the counter was thin compared with the maximum range of the beta particles. In fact the spectrum as seen in it displayed the expected peak at an energy corresponding to the passage through it of a relativistic beta particle (a typical spectrum is shown in Fig. 2) but with the expected low-energy and high-energy tails. A very unsure computation of the absolute efficiency gave $3.7\times10^{-2}$ (above the cut at channel 31 of Fig. 2 used in all work now to be reported). We accordingly determined the absolute efficiency experimentally using coincidences between the beta particles from $B^{12}$ leading to the 4.4-MeV state of $C^{12}$ and the subsequent gamma rays.

Figure 3 shows a typical singles spectrum in the NaI(Tl) crystal following $B^{12}$ decay. The 4.4-MeV peak is clearly seen on a background due chiefly to inner and outer bremsstrahlung and to the neutron background of the machine and to the beam interrupted on the first shutter. In order to analyze this spectrum it was important to know the shape of a 4.4-MeV line as seen in this crystal in these conditions of surrounding apparatus, absorption, and rather heavy all-round shielding. We accordingly simply exchanged the target for a thick one of $N^{15}$, leaving everything else the same, and, by

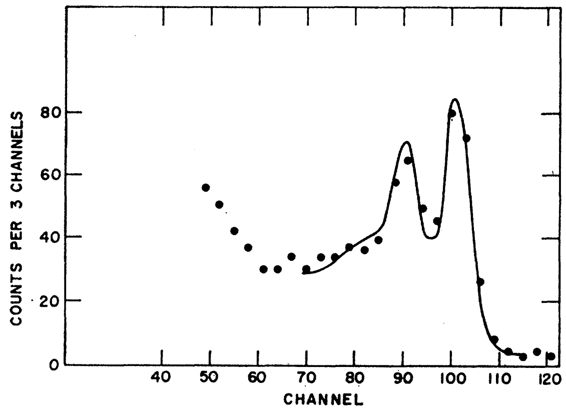


FIG. 5. Spectrum seen in the 5-in.×5-in. NaI(Tl) counter in coincidence with positron pulses in the plastic scintillator. $N^{12}$ decay. The solid line shows the expected distribution in the region of the peaks (taken from Fig. 4 with allowance for background in both cases).

bombarding this with protons of 1.3 MeV, obtained a practically pure 4.4-MeV spectrum following the reaction $N^{15}(p,\alpha\gamma)C^{12}$. We made the appropriate small corrections for the 13-MeV radiation due to $N^{15}(p,\gamma)O^{16}$ that we measured at the same time and used the residual spectrum for the interpretation of Fig. 3 and others involving the same radiation. The smoothly extrapolated background of Fig. 3 leaves a spectrum of just the expected shape and we can, therefore, interpret with confidence the singles gamma counting rate in the $B^{12}$ decay. We simultaneously measured the beta singles spectrum (as in Fig. 2) and counting rate. We then measured the gamma spectrum seen in the NaI(Tl) counter in coincidence with the beta counter above the bias corresponding to channel 31 in the spectrum of Fig. 2. A typical coincidence spectrum is shown in Fig. 4. This was interpreted as before and gave an absolute efficiency of $3.5\times10^{-2}$ for the beta counter by comparison with the singles spectrum. This figure, which agrees better with the computed efficiency than is reasonable, assumes that the beta-gamma angular correlation is isotropic and this is very nearly true since the transition is an allowed one. It also assumes that the efficiency of the beta counter above the cut at channel 31 is the same for the beta particles that lead to the ground state (maximum energy 13.4 MeV) and for those that lead to the first excited state (maximum energy 9.0 MeV). This assumption is quite a good one since the plastic detector is much thinner than the range of the great bulk of the beta particles from either transition.

Similar calibration measurements could not be performed accurately using the $N^{12}$ decay due to the much greater importance in that case of the neutron background from the machine and the intercepted beam. A consistency test was applied, however, by measuring beta-gamma coincidences from $N^{12}$. A typical spectrum so observed, corresponding to Fig. 4 for $B^{12}$, is shown in Fig. 5. By comparing such spectra for $N^{12}$ and $B^{12}$ with the respective counting rates in the beta counter and assuming that the beta-counter efficiency is the same for the two relevant positron transitions in $N^{12}$ (end points 16.5 and 12.1 MeV) we may derive the relative $N^{12}$ and $B^{12}$ branching ratios to the 4.4-MeV state of $C^{12}$. We find ($N^{12}$ branching ratio)/($B^{12}$ branching ratio) $=1.72\pm0.15$. Here the quoted error includes the estimated errors in interpreting the spectra, statistics, and so on, but makes no allowance for the possible differing beta efficiencies. This figure agrees well with the best value in the literature[5] namely $1.84\pm0.1$. We have not attempted to compute accurately the branching ratios themselves because of the rather large and uncertain

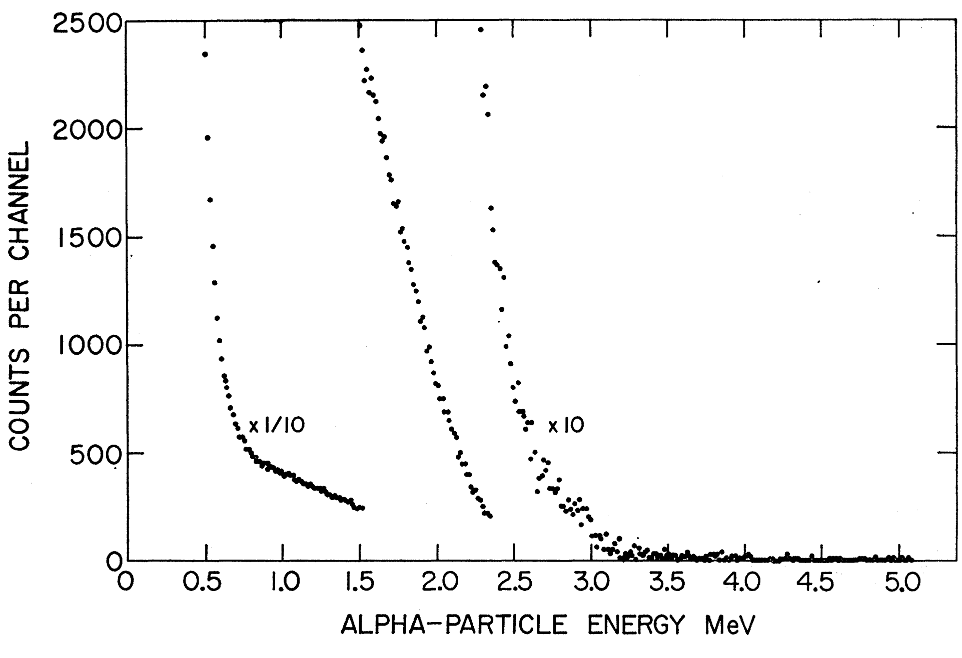


FIG. 6. Alpha-particle spectrum following $B^{12}$ decay as seen in the solid-state counter. (The highest energy alpha particle energetically possible following $B^{12}$ decay is of 4.2 MeV.)

absorption corrections associated with the heavy shielding of the gamma crystal and with its complicated geometry. A rough calculation gave about the expected results. In the subsequent analysis we assume that the efficiency of the beta counter is the same for all beta transitions with which we deal.

A comment is necessary at this point on the behavior of the beta counter. During the work with $B^{12}$ the background in it, measured by cutting the beam off the target by stopping the first shutter but leaving the machine running, was totally negligible and the correct half-life for $B^{12}$ was found by examining the time distribution of counts between irradiation bursts during normal running. This was done by narrowing the counting gate to 2 msec and moving it over the available 16-msec interval between irradiation pulses. With $N^{12}$, however, there was some background when the $He^3$ beam was cut off by the first shutter. This background decayed with an apparent half-life of about 50 sec and was due to unidentified bodies. It was carefully studied and implied a correction of 10% to the observed counting rate in the beta counter for the particular combination of irradiation, wait, and count period that we adopted. After this correction, sensibly constant during the count period, had been made the residual activity displayed the correct $N^{12}$ period.

The observed alpha-particle spectra following $B^{12}$ and $N^{12}$ decays are shown in Figs. 6 and 7. Rough half-life measurements were made on both sets of alpha particles: that associated with $B^{12}$ gave $24\pm4$ msec; that associated with $N^{12}$ gave $11\pm4$ msec. These measurements were taken as confirming the association of the alpha spectra with the respective beta emitters.

## DISCUSSION

The alpha spectrum from $B^{12}$ may be compared with that in the literature[2] from the California Institute of Technology. The experimental conditions were slightly different in the two experiments but the earlier distribution (in terms of momentum) transforms quite accurately into our (energy) distribution. (We may note an advantage of the present method in that no correction for the charge state of the particles is needed as against the situation for the magnetic spectrometer work of the California Institute of Technology.) We have compared the distributions only down to an alpha-particle energy of 0.8 MeV below which energy the distribution rises rapidly owing to the detection of the particles from the breakup of the recoil $Be^8$ ground state. In our case this distribution becomes mixed at some stage with pulses from beta particles; we made no attempt to separate these components. We conclude that our distribution is consistent with the earlier one and so our conclusions as to its explanation in terms of states of $C^{12}$ must be the same as that of the earlier workers so long as we confine ourselves to the bulk of the distribution only. However, the present experiment, with its much better statistics, reveals a significant high-energy tail to the spectrum, the importance of which is brought out clearly by the study of the $N^{12}$ decay that we now examine and which is not explained by the earlier[2] parameterization.

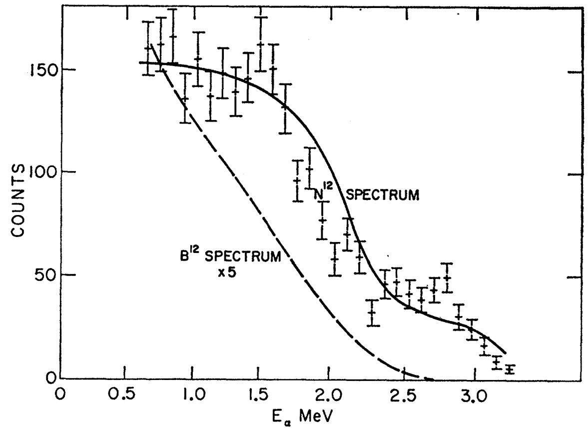


FIG. 7. Alpha-particle spectrum following $N^{12}$ decay as seen in the solid-state counter. Also shown is the spectrum following $B^{12}$ decay (taken from Fig. 6) for the same number of beta disintegrations as for $N^{12}$. The effect of transforming the $B^{12}$ spectrum to the conditions of $N^{12}$ decay by taking account of the different energetics and total decay rates and applying charge-symmetry is shown by the solid line that runs through the experimental points. No arbitrary normalization is involved in this comparison.

Our first step in the analysis of the alpha-particle spectrum following $N^{12}$ decay is to test for its consistency with that following $B^{12}$ decay assuming charge symmetry. As seen from Fig. 7 the two spectra, normalized to the same number of decaying nuclei, are radically different: that from $N^{12}$ extends to much higher alpha-particle energies and contains many more particles. This we expect qualitatively, as we have already remarked, due to the considerably greater energy available in the $N^{12}$ decay. We must now examine the situation quantitatively.

The comparison of the spectra is difficult to make accurately owing to the considerable penetration into the target backing of the recoil $B^{12}$ and $N^{12}$ nuclei (the deuteron and $He^3$ bombarding energies were both 2.4 MeV) and the consequent degradation of the alpha-particle spectra. The spatial distributions of the decaying sources were estimated using the following information: (i) the relative yields and angular distributions of the protons in the $B^{11}(d,p)B^{12}$ reaction to the various particle-stable states, which have been measured at nearby deuteron energies[9]; (ii) the center-of-mass distribution of the ground-state neutrons from $B^{10}(He^3,n)N^{12}$ which is effectively isotropic as measured at a bombarding energy of[10] 2.54 MeV (only the ground state of $N^{12}$ is heavy-particle-stable); (iii) the range-energy relations for heavy ions in which we followed the methods derived in a recent survey of the available data.[11]

[9] D. J. Pullen (private communication).

[10] F. Ajzenberg-Selove, M. L. Bullock, and E. Almqvist, Phys. Rev. **108**, 1284 (1957).

[11] E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **129**, 2180 (1963).

The procedure was first, to discover by trial and error a "true" alpha-particle spectrum following the $B^{12}$ decay which, when smeared according to the computed source distribution, reproduced that of Fig. 6; second, to transform this "true" spectrum from $B^{12}$ into a "true" spectrum from $N^{12}$ assuming charge symmetry, the known mass values[4] and using the correct Fermi phase-space function[12] $f(W)$ that reduces to $W^5$ at high energies; third, to smear this "true" $N^{12}$ spectrum appropriately for the distribution of $N^{12}$ sources. A necessary correction to this procedure was to allow for the contribution in both spectra of the alpha particles from the breakup of the recoil $Be^8$ including the possibility, by no means negligible owing to the large solid angle subtended at the target by the solid-state detector and the low decay energy of the $Be^8$ ground state, that both alpha particles from this breakup may enter the detector. (This last point was also taken into account above in comparing our $B^{12}$ spectrum with that from the earlier work.[2]) When this is done, there results the solid line of Fig. 7, the expected experimental alpha-particle distribution if charge symmetry holds. (In this prediction we use the empirical $B^{12}$ and $N^{12}$ total decay rates.) It is important to realize that there are no free parameters or arbitrary normalization in this comparison: the solid line passing through the $N^{12}$ distribution is an absolute prediction from the $B^{12}$ spectrum in both form and intensity. Although the agreement between the $N^{12}$ spectrum and the prediction from $B^{12}$ is not perfect, it is remarkably close and the discrepancies are easily attributable to the uncertainties that attend the lengthy and complicated chain of computations that link the spectra.

The degree of quantitative agreement between the observed and expected $N^{12}$ spectra cannot immediately be expressed in terms of the mixing-in to $C^{12}$ of a $T=1$ component (assuming that $B^{12}$ and $N^{12}$ are relatively pure $T=1$ nuclei) such as we have seen we should anticipate, since we have no idea as to what the beta-decay matrix element to the $T=1$ contamination might be relative to that to the chief $T=0$ component. If, however, we are prepared to assume the two transitions to be of roughly equal strength we may make a statement. The crucial point is that the transitions to the two isotopic spin components are coherent but that there is a change in relative sign of the two matrix elements to the two components when we go from $B^{12}$ to $N^{12}$ because the Clebsch-Gordan coefficients in the isotopic spins have the same sign for the transitions from $N^{12}$ and $B^{12}$ to the $T=0$ component of $C^{12}$ but opposite signs for the transitions to the $T=1$ component of $C^{12}$. We, therefore, expect, roughly, that the two $N^{12}$ distributions, experimental and computed from $B^{12}$ assuming charge symmetry, will diverge by a factor of $[(1+\alpha)/(1-\alpha)]^2$ in intensity where $\alpha$ is the amplitude of the admixture of $T=1$ into $C^{12}$. This situation is similar to one discussed in another context.[13] $\alpha=0.1$, an admixture of only 1% by intensity, would give a factor of discrepancy of 1.5 which seems to be excluded with fair certainty from the comparison in Fig. 7. This result, it must be repeated, is based on the guess of comparable intrinsic speeds for the two transitions, to the regular and to the impurity components of the isotopic spin make-up of $C^{12}$ at this excitation. Since the over-all transition is rather a fast one ($\log ft \approx 4.3$), it may well be that the transition to the $T=1$ component of $C^{12}$ is not as fast as that to the chief component and so the limit on $\alpha$ may be somewhat greater than the present estimate.

Is it a little surprising that this region of $C^{12}$ should have so low an isotopic spin impurity? The situation for states that are nucleon-unstable is that an empirical relation[14] connects the reduced width and the magnitude of the effective off-diagonal Coulomb matrix element $H^c$: reduced widths in the range 0.1–1 single-particle units imply $H^c$ values in the range 0.1–1 MeV. If these systematics extend to alpha-particle reduced widths also, as there is some indication, we should be surprised if our $C^{12}$ region showed $H^c<0.1$ MeV. Now $\alpha=H^c/\Delta E$, where $\Delta E$ is the spacing, in the present case, between the $T=0$ region of $C^{12}$ in question and the contaminating $T=1$ states, so $\alpha<0.1$ is quite consistent with $H^c\approx 0.1$ MeV or a little larger since $\Delta E$ is at least 6 MeV or so. (The first $T=1$ state of $C^{12}$ is that at 15.1 MeV and it is clear from the level scheme of $B^{12}$ that no $J=0^+$ $T=1$ state can be expected in $C^{12}$ for another 2.6 MeV at least, i. e., there can be none below an excitation of about 17.7 MeV unless there is a large level shift between $B^{12}$ and $C^{12}$.) A high degree of isotopic spin purity in our region of $C^{12}$ is, therefore, not necessarily surprising since a Coulomb matrix element even approaching 1 MeV can be tolerated. As we have remarked earlier, the extreme alpha-particle model for the present case leads us to expect a quite good isotopic spin purity such as is suggested by these results.

The absolute calibration of the beta counter yields a branching ratio to this 9–12 MeV region of $C^{12}$ in the decay of $B^{12}$ of $(7\pm2)\times10^{-4}$. The error in this figure derives chiefly from ignorance as to the true form of the alpha-particle spectrum—see later. This compares rather poorly with the earlier figure[2] of $(1.3\pm0.4)\times10^{-3}$. We offer no explanation for the discrepancy. Our branching ratio, together with the previous[2] parameterization for the $C^{12}$ state involved in the decay, implies $\log ft\approx4.4$ for the beta decay. The corresponding branching ratio in the $N^{12}$ decay as found in the present work is $(4.4\pm1.5)\times10^{-3}$. It should be noted that these absolute figures for the $B^{12}$ and $N^{12}$ branching ratios to the 9–12 MeV region are similarly affected by possible errors in the estimation of the alpha and beta counting efficiencies

[12] See, for example, E. Feenberg and G. Trigg, Rev. Mod. Phys. 22, 399 (1950).

[13] F. C. Barker and A. K. Mann, Phil. Mag. 2, 5 (1957).

[14] D. H. Wilkinson, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by M. H. Lipkin (North-Holland Publishing Co., Amsterdam, 1958), p. 175.

and that such errors would cancel out in the comparison of the alpha-particle spectra for testing charge symmetry in the two decays.

We now discuss in detail the $N^{12}$ spectrum as displayed in Fig. 7. We do this first of all in terms of ordinary states of $C^{12}$. We have already remarked that, because of the consistency of our $B^{12}$ spectrum with that published earlier,[2] the earlier analysis for the bulk of the spectrum, namely, in terms of a single $C^{12}$ level centered on 3.0 MeV (above $Be^8+\alpha$) and with a reduced width of $\theta^2=1.5$ single-particle units (defined relative to $3\hbar/2MR^2$ with $M$ the reduced mass and $R=1.45\times(A_1^{1/3}+A_2^{1/3})=5.21$ Fermis) applies equally to our results. However, considerable variations of the parameters are possible to satisfy the bulk of the distribution and this set does not give any account of the low-intensity high-energy tail to the $B^{12}$ spectrum of Fig. 6 that, because of the $W^5$ factor, becomes much more prominent in $N^{12}$, as seen in Fig. 7 where it forms a possible shoulder or even a high-energy group. We have, therefore, fitted the $N^{12}$ distribution *ab initio*. We have assumed that the $C^{12}$ decay is only to the ground state of $Be^8$; decay to the broad $J=2^+$ state at about 3 MeV will presumably, assuming the present state to be of $J=0^+$, be strongly inhibited by the Coulomb and centrifugal barriers. The best over-all fit to a single level is shown in Fig. 8: The resonance energy is 5.0 MeV above $Be^8+\alpha$ and the reduced width $\theta^2=2.6$ single-particle units (assuming that the level is $J=0^+$). This high value of $E_r$ is necessary to give any sort of account of the high-energy region around alpha-particle energies of 2.5 to 3 MeV. So broad a level would scarcely be expected to show up in other reactions; its definition in the present experiment is due entirely to the rapid fall of $f(W)$ as the excitation in $C^{12}$ increases. The large reduced width is not necessarily a stumbling block to acceptance of this parameterization since the extreme alpha-particle model of three equivalent closely-associated alpha particles would have an expected width of several single-particle units. Figure 8 shows the point at which the contribution becomes important from both alpha particles of the recoil $Be^8$ breakup entering the counter and also the corresponding point for contribution from single alpha particles of the breakup.

The fit of Fig. 8 described by the above parameters is a possible one but is not very satisfactory: it predicts too many counts at very high energies, it does not reproduce the shoulder around 2.5 to 3 MeV; it runs rather too high around 2 MeV. These discrepancies may be due to statistics and to the complicated and not wholly certain character of the correction for the penetration of the $N^{12}$ into the target backing. A more satisfactory fit may be obtained by recognizing the 2.5- to 3-MeV shoulder as due to the population of a separate state in $C^{12}$. A good account is then given by the earlier[2] set of parameters for the state responsible for the bulk of the spectrum (resonance energy 3.0 MeV above $Be^8+\alpha$) plus a state at 11.8 MeV in $C^{12}$ that gives the shoulder

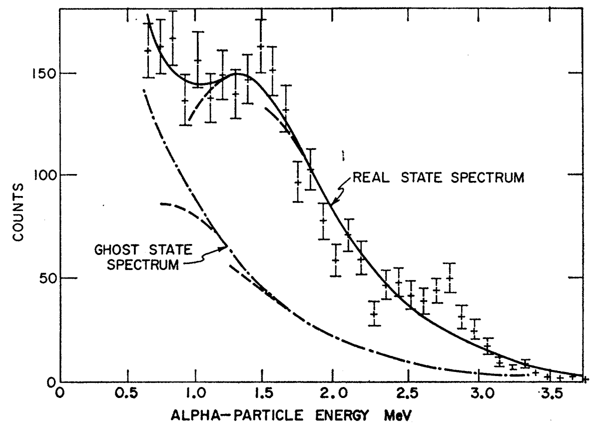


FIG. 8. Alpha-particle spectrum following $N^{12}$ decay (as in Fig. 7) fitted (solid line) with the theoretical spectrum derived from a single level at a resonance energy of 5.0 MeV above $Be^8+\alpha$ and with a reduced width of 2.6 single-particle units. The dashed curve that leaves the solid curve at about 1.8 MeV indicates the onset of contributions to the solid curve of the breakup of the recoil $Be^8$ with both alpha particles entering the solid-state counter; similarly the dashed curve that leaves the solid curve at about 1.2 MeV corresponds to the entry into the solid-state counter of single alpha particles from this break-up. The solid curve is always the sum of all these contributions. The dashed-dot curve shows the computed spectrum due to the "ghost" of the 7.66-MeV state as discussed in the text. The dashed curves attached to the dashed-dot curve have the same significance as those attached to the solid curve.

by decaying to the ground state of $Be^8$. (The shoulder has the correct shape to correspond to the calculated $N^{12}$ penetration for a narrow level in $C^{12}$.) If this interpretation is correct, the branching ratio to the 11.8-MeV state is $6\times10^{-4}$ and the corresponding $\log ft\approx4.6$ which is eminently reasonable for an allowed transition, and which fixes the parity of the state as even; $J=0,2^+$. In fact there is a well-established[4] state at $11.81\pm0.05$ MeV but nothing is known about its other properties. We may notice here that the independent-particle model in intermediate coupling[15,16] predicts a $J=0^+$ state at about 12 MeV. This may be thought to be the broad state of the present investigation. Indeed the independent-particle model state at about 12 MeV contains a very strong component (about 50% in intensity)[16] that belongs to the partition [444] and so has a large theoretical reduced alpha-particle width to the ground state of $Be^8$. Unfortunately the components connecting it by beta decay to $B^{12}$–$N^{12}$ are weak and so the theoretical $ft$ value will be low in contradiction with experiment. Because of the low alpha-particle width of the independent-particle model state we cannot associate it with the 11.81-MeV state either and, in any case, the beta decay, if it indeed feeds that state, is too strong. $J=2^+$ would perhaps be preferable for the 11.81-MeV state from the point of view of its width. In this case we may get some breakup to the broad $J=2^+$ first excited state of $Be^8$ which would give a contribution to lower regions of the

[15] D. Kurath, Phys. Rev. **101**, 216 (1956).

[16] J. M. Soper (private communication). We are grateful to Dr. Soper for this information.

alpha-particle spectrum. We cannot, of course, allow for this possibility in our analysis but such breakup cannot be very strong because the $\log ft$ value derived neglecting it is already quite low. Although the interpretation in terms of two states seems a little favored over the single broad level we do not feel able to choose between them with confidence. Better data, in particular with a thin source, are needed to establish this point. The independent-particle model gives no $J=2^+$ $T=0$ state anywhere near 12 MeV.[15,16]

It seems likely that the $J=0^+$ state of the independent-particle model will go undetected if it is indeed in the same energy region that we discuss here. The only thing that gives any sort of distinction to the present broad state is the "$W^5$" factor in the beta-decay probability: population by heavy particles would cover an even broader region of excitation, correspondingly more difficult to analyze; the overlaying by the present state will be a serious obscuration unless by chance a reaction turns up that populates the independent-particle model state strongly and the present state weakly. It is rather disturbing that $C^{12}$ shows at least two states (the $J=0^+$ states at 7.66 and 9–12 MeV) and maybe one more (that at 11.8 MeV) all of even parity and strongly connected to $B^{12}-N^{12}$ by beta decay but not belonging to $p^8$ of the independent-particle model. Double excitation would in general be expected to be associated with rather feeble beta decay if $p^8$ is anything like correct for $B^{12}-N^{12}$. (Note that the 7.66-MeV state cannot be the independent-particle model state in question, first, because it is 4 MeV too low in energy, and second, because of the fast beta decay to it[1]—$\log ft=4.2$.)

We may finally note that alpha particles of energy in the region of the shoulder at 2.5–3 MeV would result from the decay of the $T=1$ $J=1^+$ state at 15.1 MeV to the broad $J=2^+$ state of $Be^8$ at about 3 MeV. However, although the beta transition to the 15.1-MeV state would be superallowed, since it is the central member of the $B^{12}$-$C^{12}$-$N^{12}$ lowest $T=1$ triplet, the transition would be far too weak, because of the small energy release, to account for the spectrum in the region of the shoulder. Further confirmation of this comes from the mutual consistency, including the shoulder, of the $B^{12}$ and $N^{12}$ spectra as displayed in Fig. 7: The 15.1-MeV state is not accessible to the decay of $B^{12}$.

It remains to enquire whether our observed alpha-particle spectrum following $N^{12}$ decay is consistent with the idea that it is due to the "ghost" of the 7.66-MeV level as discussed above. We have computed the expected "ghost" spectrum using the same relevant parameters as for the above interpretation in terms of true levels. For this computation we need additionally the branching ratio in the $N^{12}$ decay to the 7.66-MeV state. We have used[3] $(3.0\pm0.4)\times10^{-2}$. The result is shown in Fig. 8 as the dash-dot line. We see that the "ghost" has approximately the correct extension in energy but fails by a factor of 2 or more in intensity in the energy region above 1 MeV and has the wrong shape; in particular it shows no sign of the plateau around 1 to 1.5 MeV. Although uncertainties in the computation may be responsible for the discrepancy in intensity it seems improbable that these should give so wrong a form to the distribution (the high-energy decline of the spectrum is due chiefly to the "$W^5$" factor and so agreement on this point is not very significant). We conclude that although the "ghost" may make a substantial contribution it is unlikely to provide the whole explantion. We have not attempted to reanalyze the spectrum that would result by subtracting the calculated "ghost" spectrum from the observed points. It is clear that if this were done two levels in $C^{12}$ would be demanded, which strengthens the earlier suggestion that transitions to the 11.81-MeV level of $C^{12}$ are involved. Indeed, the rather close approach at the lowest energies displayed in Fig. 8 of the "ghost" spectrum to the experimental points implies a subtracted spectrum that would be difficult to explain by any means and this in turn suggests that the "ghost" effect may be somewhat overestimated in Fig. 8.

Notice that if the earlier figure[2] for the $B^{12}$ branch to the 9–12 MeV region of $C^{12}$ is correct and our own is smaller because of error in estimating the counters efficiencies then the charge symmetry that we have established for the $B^{12}$ and $N^{12}$ decays independent of the absolute counter efficiencies requires that the branch from $N^{12}$ be correspondingly larger than we have stated. The effect of this on Fig. 8 would be to lower the predicted "ghost" spectrum relative to the experimental points, making it less able to give an account of them and leaving the difference between it and the experimental points of a more reasonable form to be accounted for by ordinary states of $C^{12}$.

## CONCLUSIONS

We conclude:

(i) that the beta decay of $B^{12}$ and $N^{12}$ to the region of excitation in $C^{12}$ between about 9 and 12 MeV is quite accurately charge-symmetric and that the isotopic spin impurity in this region may well be as little as 1% in intensity;

(ii) that the decay is consistent with the involvement of a single very broad level at a nominal excitation of about 12.5 MeV and with a reduced width of about 2.6 single-particle units but that a somewhat preferable account is given by a broad level at lower excitation plus a state that may be the known level at 11.81 MeV in which case the transition to the latter level could have $\log ft\approx4.6$ which would fix the parity as even;

(iii) that although the contribution in this energy region from the "ghost" of the 7.66-MeV state may be considerable and comparable with the observed spectrum it is unlikely that the whole effect is due to it.